



INDUSTRIAL TECHNOLOGY CENTRE/MANITOBA RESEARCH COUNCIL

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AN INVESTIGATION OF THE CORROSION FATIGUE BEHAVIOUR
OF
MAGNETIC METALLIC GLASSES (UP-M-502)

45pp.

Final Report by:

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Work on the project was conducted under the auspices of the Canada Centre for
Mineral and Energy Technology, Energy, Mines and Resources Canada.

DSS File No. 15SQ.23440-4-9219

DSS Contract Serial No. ISQ84-00248

CANMET Project No. 705404

CANMET Scientific Authority: Dr. L. Collins

September 16, 1986

45pp

MICROMEDIA



SUMMARY

Commercially available iron based metallic glasses, Metglas 2605-S2, 2605-SC and 2826-MB, were studied for their tensile behaviour and fatigue strength in air, 3% sulfuric acid solution and 3% NaCl solution. As received ribbons (25 mm wide) were evaluated and straight length samples were used for both tensile and fatigue testing. Attempts to use scissors or electrical discharge machining for fabricating gauge caused excessive damage. Sulfuric acid solution severely corroded Metglas 2605-S2 and 2605-SC and therefore affected the tensile strength, whereas 2826-MB was not affected at all.

In fatigue tests, S-N curves similar to those of crystalline alloys were obtained with distinct fatigue limits for all alloys. Fatigue strength of 2826-MB was found to be superior to the other alloys in all environments whereas alloy 2605-SC and 2605-S2 had significant loss of fatigue strength in H_2SO_4 solution. This was attributed to severe corrosion. The fracture surfaces contained typical vein pattern and striation markings; however, no distinct single fracture initiation point could be located in these ribbons. Some unique fracture features were also noticed under SEM.

RÉSUMÉ

On a soumis trois échantillons de métal vitreux à base de fer, disponibles sur le marché - les Metglas 2605-S2, 2605-SC et 2826-MB - à des essais de traction et de résistance dans l'air, dans une solution d'acide sulfurique à 3 % et dans une solution de NaCl à 3 %. On a évalué les rubans tels que reçus (25 mm de large) et l'on a sélectionné certains échantillons pour les tests. Les tentatives de calibration en vue des essais de traction effectués au moyen de ciseaux ou de décharges électriques ont occasionnés de sérieux dégâts au matériau. La solution d'acide sulfurique a gravement corrodé les Metglas 2605-S2 et 2605-SC, et donc diminué leur résistance à la traction; quant au 2826-MB, il n'a subi aucune détérioration.

Les courbes de Wöhler obtenues lors des essais de résistance, étaient identiques à celles des alliages cristallins, mais chaque alliage présentait une limite de fatigue distincte. Le 2826-MB a démontré une résistance nettement supérieure à celle des autres alliages dans tous les milieux, alors que le 2605-SC et le 2605-S2 ont perdu énormément de leur résistance dans la solution de H_2SO_4 . Cette perte est attribuable aux effets de la corrosion. Les zones de fracture présentaient une structure veinée et des stries caractéristiques; il a toutefois été impossible d'isoler un point de fracture précis sur les rubans. En outre, à l'examen au microscope électronique à balayage, on a observé des éléments de fracture inconnus jusqu'alors.



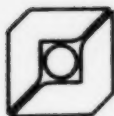
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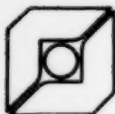
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1. INTRODUCTION

Over the past decade, the technology of rapidly solidified materials has seen a tremendous growth. Many conferences, a large number of publications and personnel devoted to this field, indicate a strong interest and great potential for these materials in today's technological world.

Metallic glasses (also called glassy alloys or amorphous metals) are non-equilibrium or metastable solids with mainly metallic chemical constituents packed in a disordered structure similar to liquids but approximately 5% denser. Generally, metallic glasses contain no crystal structure, being chemically homogeneous and structurally isotropic.

However, in practice, the amorphous structure is not easily achieved. One of the first metallic glasses were produced from Au-Si alloy in 1959 by P. Duwez and his coworkers at the California Institute of Technology. They showed that the disordered liquid structure can be "frozen" by using a cooling rate of approximately 10^6 Ks⁻¹.

This was the birth of metallic glasses. Today hundreds of alloys are produced, some on a commercial basis in quantities of tons per day. Typically, alloys containing transition metals and metalloids in various amounts are most readily formed at low melting temperature compositions such as eutectics. Because of their unique structure, metallic glasses show unusual physical properties. Amorphous alloys containing iron can be mechanically very hard yet some are ferromagnetically very soft, i.e. they can be magnetised and demagnetised with ease and with little loss of energy. Many applications of metallic glasses for electromagnetic devices are optimized compositionally with respect to properties such as high saturation magnetization, magnetic-mechanical coupling coefficients, mechanical hardness and strength. While the lack of grain boundaries and chemical homogeneity of metallic glasses favours good corrosion resistance, it is found that corrosion resistance is alloy dependent. Only alloys containing Cr and P exhibit the best corrosion properties, however, these elements also degrade magnetic properties. Thus, resistance to environmental corrosion could be one of the factors limiting the utilization and commercialization of metallic glasses in magnetic devices.

Although limited investigation has been conducted on environmental corrosion behaviour under static conditions for these alloys, very little work has been performed on the effect of dynamic stress loading on metallic glasses in corrosive environments. Most electromagnetic devices such as transformers, sensors and switches are exposed to vibration and fatigue under corrosive environments in real-life working conditions.



Therefore, this project undertook a study of tensile and fatigue behaviour of three commercially available metallic glass alloys in three corrosive environments. Corrosion and fracture behaviour of these alloys was also investigated.

2. LITERATURE SURVEY

The published literature on the subject of metallic glasses and rapidly solidified materials is growing astronomically. Initially, most of the studies have concentrated on their physics, structure, electronic and magnetic behaviour but it was soon realized that the materials have superior strength and hardness as well. They may also possess excellent corrosion resistance.

In this section, the literature covering fatigue behaviour of metallic glasses and their corrosion behaviour as related to mechanical properties will be reviewed.

The early fatigue studies on amorphous alloys were performed by US and Japanese scientists. Davis (1) first reported fatigue test data on $\text{Ni}_{39}\text{Fe}_{38}\text{P}_{14}\text{B}_6\text{Al}_3$ ribbons (1.7 mm wide x $42\mu\text{m}$ thick) with a hole of 0.1 mm in diameter in the centre of the specimen by EDM. Under fatigue loading between 620 and 210 MPa, the crack growth rate, da/dN , was found to be 10^{-5} to 10^{-4} mm/cycle.

Davis (2) further examined fatigue the properties of $\text{Ni}_{49}\text{Fe}_{29}\text{P}_{14}\text{B}_6\text{Si}_2$, $\text{Ni}_{48}\text{Fe}_{29}\text{P}_{14}\text{B}_6\text{Al}_3$ and $\text{Pd}_{77.5}\text{Cu}_6\text{Si}_{16.5}$ alloys. The Ni-Fe based samples were 0.4 to 0.7 mm wide and 26 to 76 μm thick whereas Pd-Si samples were 0.28 mm in diameter. The first alloy was tested as uniform strips, the second had a hole of 0.1 mm diameter in the centre and some had gauge sections of 0.26 mm wide x 1 mm long. Pd-Si was tested as a uniform wire with a gauge section 6 mm long x 0.18 mm diameter. A log-log plot of stress ratio (stress amplitude/tensile strength-average stress) and cycles to failure showed approximate straight lines with slopes about -0.4 for Ni-Fe alloys and -0.44 for Pd-Si. For each type of specimen, a fatigue limit was observed and the fracture morphology studies revealed a nucleation spot near the edge of the specimen within the gauge section. Periodic striations were also noted near this spot, however, chevron pattern took over the area where fast unstable growth was occurring. On a fine scale, the chevron pattern typically contained an equiaxed vein pattern indicating that local failure occurred by shear rupture. Specimens with reduced-section had a longer fatigue life by a factor of two compared to as-received samples.



The Japanese workers Ogura et al. (3) conducted fatigue studies on $\text{Pd}_{80}\text{Si}_{20}$ ribbons (0.5 to 0.7 mm wide, 20 to 25 μm thick, 2 cm long) and fatigue limit of 400 MPa (1/3 tensile strength) at 35,000 cycles or more was established. The fracture surface consisted of two parts, one part contained characteristic vein patterns while the other parts contained a plateau surrounded by sloped surfaces containing striations. Ogura et al. (4, 5) also studied crack propagation under fatigue from a precrack in a Pd-Si alloy. Crack growth rate and slip markings/spacings were established accordingly. Scanning electron micrographs of the fracture surfaces indicated slip markings in a zig-zag pattern.

Mulder et al. (6) studied fatigue properties of $\text{Co}_{75}\text{Si}_{15}\text{B}_{10}$, $\text{Co}_{58}\text{Ni}_{10}\text{Fe}_5\text{Si}_{11}\text{B}_{16}$, $\text{Fe}_{40}\text{Ni}_{40}\text{B}_{20}$ and $\text{Fe}_{63}\text{Ni}_{15}\text{Si}_{18}$ alloys and obtained stress ratio-number of cycles to failure (S-N) curves for each. Stress ratio, S, is defined as $S = S_a/(S_y - S_v)$ where S_a - stress amplitude, S_y - fracture stress and S_v - average stress. Both polished and as-received samples containing rather large pits were used for this study. For edge polished samples, a higher slope of the S-N curve was obtained. A fatigue limit at $S = 0.1$ and 10^5 cycles was established. The surface pits also reduced the fracture stress and the stress level at which the fatigue limit was reached. The fatigue limit in bending was found to be higher than that determined in tension. No detailed fractography was performed.

Chaki et al. (7) carried out fatigue crack growth, da/dN , studies on $\text{Co}_{72.15}\text{Fe}_{5.85}\text{Mo}_{2.15}\text{Si}_5$ and $\text{Co}_{76}\text{Fe}_2\text{Mn}_{4.12}\text{Si}_6$ metallic glasses to determine effect of overload on crack propagation. Samples used were straight ribbons (25 mm wide, 30 μm thick and 8 cm gauge length) with 0.5 mm long crack in the centre. Maximum loads were varied between 80 to 220 N and the load ratio was 0.1 (minimum/maximum load). Conventional S-N data was not presented, however, detailed measurements and analysis of da/dN , against stress intensity ratio, K, were carried out and compared to Davis (1, 2) data. SEM analysis of fracture surface and fatigue striations indicated that spacing between striations related well to about every hundred cycles. The fracture surface morphology had the characteristic vein pattern along with featureless regions. Special attention was paid to crack tip and shear bands propagation.

Recently, Hagiwara et al (8) studied fatigue strength of iron based (Fe-Si-B, Fe-P-C, Fe-Cr-Si-B) amorphous wires having about 120 μm diameter and they found that such wires have superior fatigue strength compared to piano wires and addition of Cr remarkably improved fatigue strength. However, ribbons of the same composition had much inferior fatigue strength. An increase in humidity also decreased fatigue strength of the wires due to corrosion. In wires, fracture initiated at a surface point and gradually progressed with striation pattern to the central region where fast fracture took place.



Corrosion behaviour of metallic glasses has been extensively studied by the Japanese group of Prof. Hashimoto (8, 9) and reviewed recently by Waseda et al. (10). Electro-chemical measurements, pitting corrosion rates and SEM has been extensively used to study the corrosion behaviour of many alloys. Earlier work indicates that an addition of about 8% Cr to glass forming Fe-base, Ni-base and Co-base alloys with metalloids elements such as P and C as one of the constituents reduces corrosion rate of metallic glasses in acidic and neutral solutions. This is attributed to the rapid formation of a uniform, stable and passive film with a high protective quality.

A great deal of attention was paid to potentiodynamic polarization curves of interest to many electrochemists and material scientists, however, very little work has been reported on the subject of corrosion fatigue. Fe-Si-B, Ni-Si-B and Co-Fe-Si-B all have poor corrosion resistance in acidic solutions. Corrosion occurs by a pitting process, especially when one surface of the ribbon is rough. Generally, corrosion resistance of metallic glasses should be enhanced, in part, due to their structural characteristics since they have no grain boundaries, segregates or crystalline defects that act as chemically active sites.

It was also noted that a small addition of Mo (<3%) to Fe-P-C alloy was more effective than chromium in reducing corrosion rate (13). Contrary to crystalline Fe-Mo alloys, the glassy alloys containing 4% or more of Mo were passivated without pitting even in 1N HCl solutions.

Latanision et al. (11) studied general corrosion features of rapidly quenched alloys, both amorphous and micro-crystalline, and concluded that not all glassy alloys were corrosion resistant; some with Cr and P had remarkable inertness. Stress corrosion cracking and hydrogen embrittlement was also shown to occur in glassy metals.

Archer et al. (12) studied stress corrosion behaviour of Fe-Ni-B alloy in aqueous acidic media and found the material quite susceptible to cracking through hydrogen embrittlement.

From limited work on fatigue behaviour of various amorphous alloys, it is evident that these materials have typical S-N curves and a fatigue limit like crystalline alloys. Fracture surfaces usually have distinct crack initiation sites, fatigue striations and vein pattern. Corrosion resistance of metallic glasses is significantly improved by addition of elements like Cr, P and Mo. However, very little data exists on corrosion fatigue behaviour of iron-based amorphous alloys.



3. EXPERIMENTAL DETAILS

3.1 Material

Metallic glass alloys with potential for commercial applications in transformers and transducers were selected for an evaluation of their behaviour under the combined conditions of high-frequency cyclic stress (unipolar) and mildly corrosive environments (H_2SO_4 and NaCl solutions).

The following metallic glass alloys containing no chromium or phosphorus were selected for this program.

<u>Alloy</u>	<u>Composition</u>
Metglas	
2605-SC	$Fe_{81}B_{13.5}Si_{3.5}C_2$
2605-S2	$Fe_{78}B_{19}Si_3$
2826-MB	$Fe_{40}Ni_{38}Mo_4B_{18}$

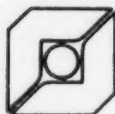
The alloys were obtained from Metglas Products, Allied Corp., USA, in the form of ribbons 2.5 cm wide and 0.0022 cm thick (under trade name "Metglas"). Examination of the cross-section of each of the three metallic glass alloys (using metallographic techniques) showed that the ribbon material had a non-uniform thickness (Figure 1) which was considered to have an effect upon the computed cross-sectional area and subsequently tensile strength of each alloy. Therefore, the minimum thickness of each alloy was measured and used in the calculations.

3.2 Sample Preparation

As the samples for tensile and fatigue test were initially planned to be the standard "dog-bone" (Figure 2a) or the "hour glass" shape (Figure 2b) to be fabricated from the 2.5 cm wide ribbon an evaluation of material cutting techniques was undertaken.

Firstly, specimens were cut with ordinary hand operated scissors which produced an unacceptable "ragged" edge (Figure 3). The second method made use of an electric discharge machine (EDM), however, this produced heat affected zones at the cut line and also produced corroded surfaces (Figure 4) due to the cooling water used. Use of a scalpel knife to cut the sample shape also proved unsuccessful in that a rough, non-uniform cut line was produced. Finally, it was decided to fabricate samples "as-received" 2.5 cm wide ribbon with a 5 cm gauge length leaving the as-produced edge of the material undisturbed.

The next step in sample preparation was to develop a method to grip and align the metallic glass specimens for true axial loading. Metal load-bearing tabs (2.3 mm thick x 25 mm square), bonded to the sides of the metallic glass specimens, on the gripped ends (Figure 5) were found



to be satisfactory. Stainless steel (304) and aluminum tabs (15.5 mm thick) were bonded to metallic glasses with quick-curing cyanoacrylate adhesives (HYSOL brands) and epoxy adhesive. The best combination was found to be aluminum and epoxy. For proper axial alignment of the samples, during tensile and cyclic fatigue testing, samples with pinned anchor points were adopted (Fig. 6). Each sample had a 3.57 mm diameter hole punched through the bonded metal tabs at each end.

A special test fixture with self-aligning anchor points for the samples was also fabricated for conducting tensile and fatigue tests in corrosive environments (Fig. 7).

3.3 Tensile Testing

Tensile tests were conducted on an Instron Universal Testing Machine incorporating the special alignment fixture (Fig. 7). Each sample was loaded to failure at an extension rate of 0.033 mm/sec.

Test samples were preconditioned for 15 min. in the testing environment before being tested in 3% (vol) H_2SO_4 and 3% (wt) NaCl solutions.

3.4 Fatigue Testing

Fatigue testing was conducted at a frequency of 50 Hz in the load control mode of a servo-hydraulic loading system manufactured by Zonic Corporation. The 50 Hz frequency was selected to closely match projected operating conditions of these alloys in transformers and transducer applications.

Straight lengths of as-received 25 mm wide ribbon with 50 mm gauge section were again used for fatigue testing in air, 3% (vol) H_2SO_4 and 3% (wt) NaCl solutions.

All samples were preconditioned in the corrosive environment for 15 minutes prior to testing in the solutions (Fig. 8). A preload of 222 N was applied to remove any slack in the loading system.

After completion of tests, samples were washed and air dried prior to storage in separate plastic bags for later S.E.M. examination. Fatigue tests for each alloy were carried out at various stress levels depending upon the value of fracture stress. Tests were terminated either when the sample failed or reached 10^6 cycles.

To assess the corrosion behaviour of these alloys in corrosive solutions under static conditions, corrosion rate was determined by "loss of weight" technique. Specimens were weighed before and after immersing them for up to 90 hours in the solution and measuring the weight loss.



3.5 SEM Examination

As received samples, cut edges and corroded samples were examined by a JEOL scanning electron microscope (SEM). Fracture surfaces of some samples were also analyzed in detail in order to assess the fracture initiation and propagation. Crack growth, however, was not monitored.

4. RESULTS AND DISCUSSIONS

The three alloys, obtained as one inch wide ribbons, were similar in their surface finish. The dull side of the ribbon contacting the wheel surface contained many pits due to air entrapment, whereas the shiny side was smooth (Fig. 9). However, all ribbons contained a fish-scale pattern on the shiny side typical of many metallic glass ribbons (Fig. 9b). The composition of the alloys was supplied by the manufacturer and it was assumed that ribbons were amorphous in atomic structure.

The cross-section of each of these ribbons was examined and as shown in Fig. 1, alloy 2605-S2 contained large pits which reduced the cross-sectional area significantly. Other ribbons had fairly uniform thickness. This variation in thickness had to be accounted for in stress calculations, therefore, only "minimum" thickness was used for such purposes (Table I).

Various cutting methods that were attempted to fabricate samples revealed that excess damage was introduced to specimen edges (Fig. 3 and 4) which could affect tensile and fatigue properties of the material. Therefore, it was decided to test the samples in "as-received" condition which represented true material to be used in commercial applications.

The ultimate tensile strength and fracture stress of the three alloys were determined in air, NaCl solution and H_2SO_4 solution. The samples fractured in linear elastic manner without showing any yielding. The test results are given in Tables II-IV. 2605-S2 alloy was strongest in air (3174 MPa) whereas 2605-SC gave the lowest fracture stress (2290 MPa). The tensile strength of Alloy 2826MB was not affected by the environment, but alloys 2605-S2 and 2605-SC showed a loss in strength specially in H_2SO_4 solution. This could be due to corrosion of the surface by this solution during the tests.

To check the effect of environment, the corrosion rate of these alloys was determined in H_2O , 3% NaCl and 3% H_2SO_4 solutions. The results of the corrosion test are given in Table V. It can be seen that both Alloys 2605-SC and 2605-S2 corroded rapidly in H_2SO_4 solution with heavy pitting which occurred preferentially in a fish scale pattern (Fig. 10). The presence of nickel and molybdenum in 2826 MB reduced corrosion rate in H_2SO_4 solution.



Distilled water and NaCl solutions did not affect the tensile properties of any of the alloys significantly.

An extensive fatigue testing program was undertaken for each alloy in three environments - air, 3% NaCl and 3% H₂SO₄ solution. Sinusoidal cyclic stress was applied to the samples while a constant minimum load of 222 N was maintained in all tests. Maximum stress, S_m , was raised to achieve higher stress levels (or higher mean stress levels, S_v). For each metallic glass sample, S_m is plotted against number of cycles (N) to failure in each medium (Fig. 11-13). It can be seen that S_m - N curve is similar to that of metallic crystalline materials with a definite slope and levelling off of S_m for 10^5 - 10^6 cycles.

There is less scatter in data for 2826MB Alloy (Fig. 13) compared to the others. This could be due to uniformity in thickness and better quality of ribbons for 2826 MB Alloy. Fatigue life of both 2605-S2 and 2605-SC is reduced in H₂SO₄ solutions, however, carbon-containing 2605-SC was significantly affected (Fig. 12).

Typical S-N curves, generally used to represent fatigue test results are plotted in Fig. 14-16. S is defined as $S_a/S_y - S_v$ where S_a = stress amplitude, S_y = fracture stress and S_v is the mean stress. The data has been plotted for each of the three environments. It can be seen that Alloy 2826-MB has the best fatigue strength in all environments. Again this can be attributed to corrosion resistance of this alloy due to presence of nickel and molybdenum.

The results of these fatigue experiments on as received samples generally agree (Fig. 14) with the few data available in the literature (1-6). However, data can only be compared for tests in air where the fatigue limit is about $S = 0.06$ and at $N = 10^5$ cycles. This is well below the limits of typical high strength steel (1), but relatively high in comparison to other materials. Moreover, the slope of S-N curve is much steeper compared to H-S steels. This implies that metallic glasses in general are poor in structural applications requiring fatigue loading. However, Hagiwara et al (7) demonstrated that Fe-Si-B, Fe-P-C wires have superior fatigue strength than piano wire and amorphous ribbons of same composition. The poor performance of metallic glass ribbons in fatigue can be attributed to surface irregularities like pits, fish scale pattern and rough edges, high residual stresses and low ductility.

Fatigue limits get much worse in H₂SO₄ solution where it reaches $S = 0.02$ for 2826 MB at 5×10^5 and $S = 0$ at 3×10^5 and 1.5×10^4 for 2605-S2 and 2605-SC respectively (Fig. 16).

Fracture surfaces of broken fatigue samples were examined under a scanning electron microscope. It should be noted here that samples were as received (one inch wide) with no intentional point of crack initiation. This is quite different from previous investigations (1, 2, 7) where either samples were small (2 mm wide) or intentional cracks were introduced into the specimens.



The majority of samples broke at 45° to the tensile axis, however, the fracture path was not straight. A large fraction of the fracture surface was covered with a vein pattern typical of amorphous materials (Fig. 17a). But areas within these vein patterns seem to contain fatigue striations (Fig. 17b). Both micrographs relate to 2605-S2 tested in air. Zones of rapid fracture are indicated by chevron pattern (Fig. 17c). Such features have also been observed by other investigators (1, 2, 7). Besides these features, certain other peculiarities were also noted, for example, a localized ductile fracture (Fig. 18a), a stepwise fracture (Fig. 18b) and fatigue striations with no vein pattern in 2826MB (Fig. 18c).

Examination of corrosion-fatigued samples indicated similar features except that some areas were corroded. For metallic glass 2605-SC tested in H_2SO_4 solution, Fig. (19a) shows a vein pattern with fatigue striations whereas Fig. (19b) shows an area of vein pattern either corroded or containing porosity. This area is just left of a dimple in cross-section (Fig. 19c) when fast fracture (chevron pattern) starts. Such dimples come from trapped air bubbles and probably initiate fast fracture.

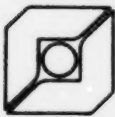
Similar features were noted for 2605-SC fatigue tested in NaCl solution (Fig. 20a, b, c). Again surface defects cause fast fractures (Fig. 21).

In all ribbon specimens, no specific fatigue crack initiation site could be observed. These specimens had a large surface area compared to wire specimens studied previously and the fracture path wasn't straight. As mentioned earlier the cross section of ribbons was not uniform and the presence of several types of fracture morphology indicates that microstructure of the ribbon is not uniform either. It is very difficult to say if deterioration of fatigue properties of samples in H_2SO_4 was caused by general attack or hydrogen embrittlement. In most cases, except for a downward shift, S-N curves were maintained indicating that a general chemical attack by H_2SO_4 may be the main reason.

SEM examination of corroded specimens did not reveal any distinct fracture features different than those tested in air.

5. CONCLUSIONS

1. Surface finish of two commercially produced Metglas ribbons 2605-S2 and 2605-SC contained defects like fish-scale pattern whereas the alloy 2605-S2 had significant variation in thickness. These features affected corrosion behaviour as well as strength of the material.
2. Some of the cutting methods, like using scissors and electrical discharge machining introduced damage to the metallic glass edges and were found unsuitable for sample preparation.



3. The or fracture strength of 2605-S2 and 2605-SC was reduced in 3% H_2SO_4 solution whereas NaCl solution did not affect the strength significantly.
4. Weight loss measurements indicated 100 times higher corrosion rate (10^{-4} gm/cm²/hr) for 2605-S2 and 2605-SC alloys in H_2SO_4 solution than for alloy 2826 MB containing Ni and Mo.
5. Alloy 2826 MB exhibited superior fatigue properties which were not affected by H_2SO_4 and NaCl solutions. Alloy 2605-SC and 2605-S2 lost significant fatigue strength in H_2SO_4 solution. However, all three ribbons had much lower fatigue strength compared to a high strength steel.
6. SEM examination of fracture surfaces of fatigued specimens indicated typical striations and areas of fast fracture with chevron markings. Due to internal defects, there appears to be several points of crack initiation in one inch wide ribbon specimens.

Therefore, the alloys 2605-SC and 2605-S2 which are superior in magnetic and electrical properties, have poor corrosion resistance and fatigue strength in H_2SO_4 environment. Their applications as force transducers or other sensors in atmospheres containing SO_2 and humidity have to be limited and perhaps, alloys 2826 MB or Cr containing metallic glasses should be used.



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- 12 -

Table I

RESULTS

Thickness of metallic glass alloy ribbon samples as determined by optical microscopy.

	<u>Variation in Thickness</u>
#2826-MB = 0.022 mm	+0.0011 -0.0000
#2605-S2 = 0.013 mm	+0.0095 -0.0000
#2605-SC = 0.019 mm	+0.0037 -0.0000



Table II: Tensile Tests in Air

Material Designation	Failure Load		Ult. Tensile Stress	
	Kg	lb	mPa	psi
2826-MB	150	337	2515	364835
	139	307	2326	337363
	154	340	2576	373626
Average	148	328	2472	358488
2605-S2	111	245	31188	462264
	112	238	3227	467925
	114	252	3279	475471
Average	112	248	3231	468543
2605-SC	115	254	2305	334210
	120	265	2405	348684
	108	239	2169	314474
Average	114	253	2293	332485



Table III: Tensile Tests in 3% (vol) H₂SO₄ Solution

Material Designation	Failure Load		Ult. Tensile Stress	
	Kg	lb	mPa	psi
2826-MB	159	351	2660	385174
	127	281	2130	308791
	160	354	2683	389011
Average	149	329	2491	361172
2605-S2	88	194	2524	366038
	98	217	2824	409434
	103	228	2967	430189
Average	96	213	2772	401892
2605-SC	104	230	2087	302632
	87	192	1742	252632
	103	228	2069	300000
Average	98	217	1966	285070



Table IV: Tensile Tests in 3% (wt) NaCl Solution

Material Designation	Failure Load		Ult. Tensile Stress	
	Kg	lb	mPa	psi
2826-MB	161	356	2698	391209
	159	351	2660	383714
	152	336	2546	369231
Average	157	348	2635	382075
2605-S2	111	245	3188	462264
	108	239	3110	450943
	110	243	3162	458491
Average	110	242	3153	457233
2605-SC	103	228	2069	300000
	109	241	2187	317105
	77*	170*		
Average	106	234	2128	308551

* Deleted value. Sample broke/pulled out of anchor tab.



Table V: Corrosion Rates in Different Solutions

Alloy	Solution	Corrosion Rate. g/cm ² -hr
2605-S2	H ₂ O	6.9 x 10 ⁻⁶
	3% - NaCl	10.6 x 10 ⁻⁶
	3% - H ₂ SO ₄ **	2.6 x 10 ⁻³
2826-MB	H ₂ O	3.2 x 10 ⁻⁶
	3% - NaCl*	3.67 x 10 ⁻⁶
	3% - H ₂ SO ₄ **	8.05 x 10 ⁻⁶
2605-SC	H ₂ O	8.24 x 10 ⁻⁶
	3% - NaCl*	10.4 x 10 ⁻⁶
	3% - H ₂ SO ₄ **	1.38 x 10 ⁻⁴
* % wt. ** % vol.		



250x

Figure 1: Non-Uniform Cross-
Section of a Metallic
Glass

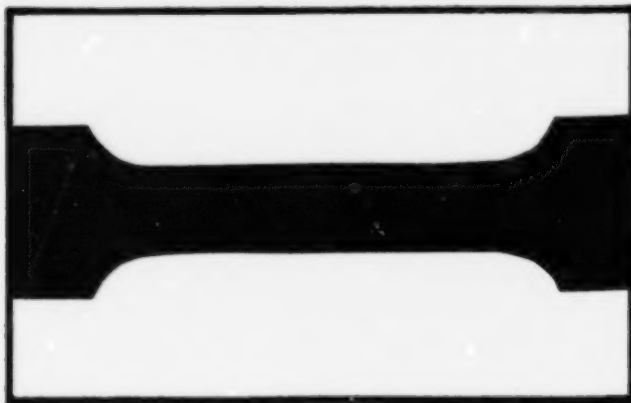


Figure 2a: Standard Dog-Bone
Shape of Samples

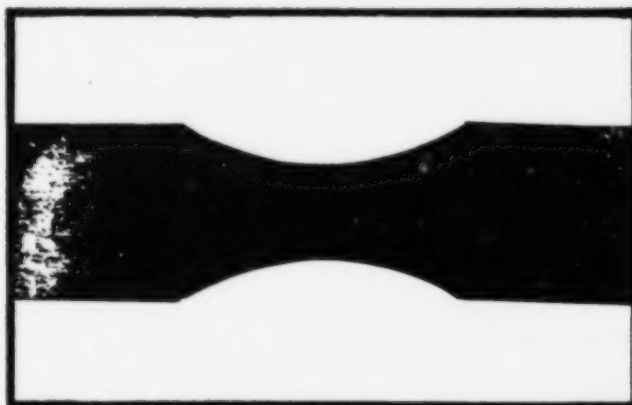


Figure 2b: "Hour-Glass" Shape of
The Test Sample



Figure 3: Edge Cut with Scissors,
A Shear Band is Produced
on the Surface

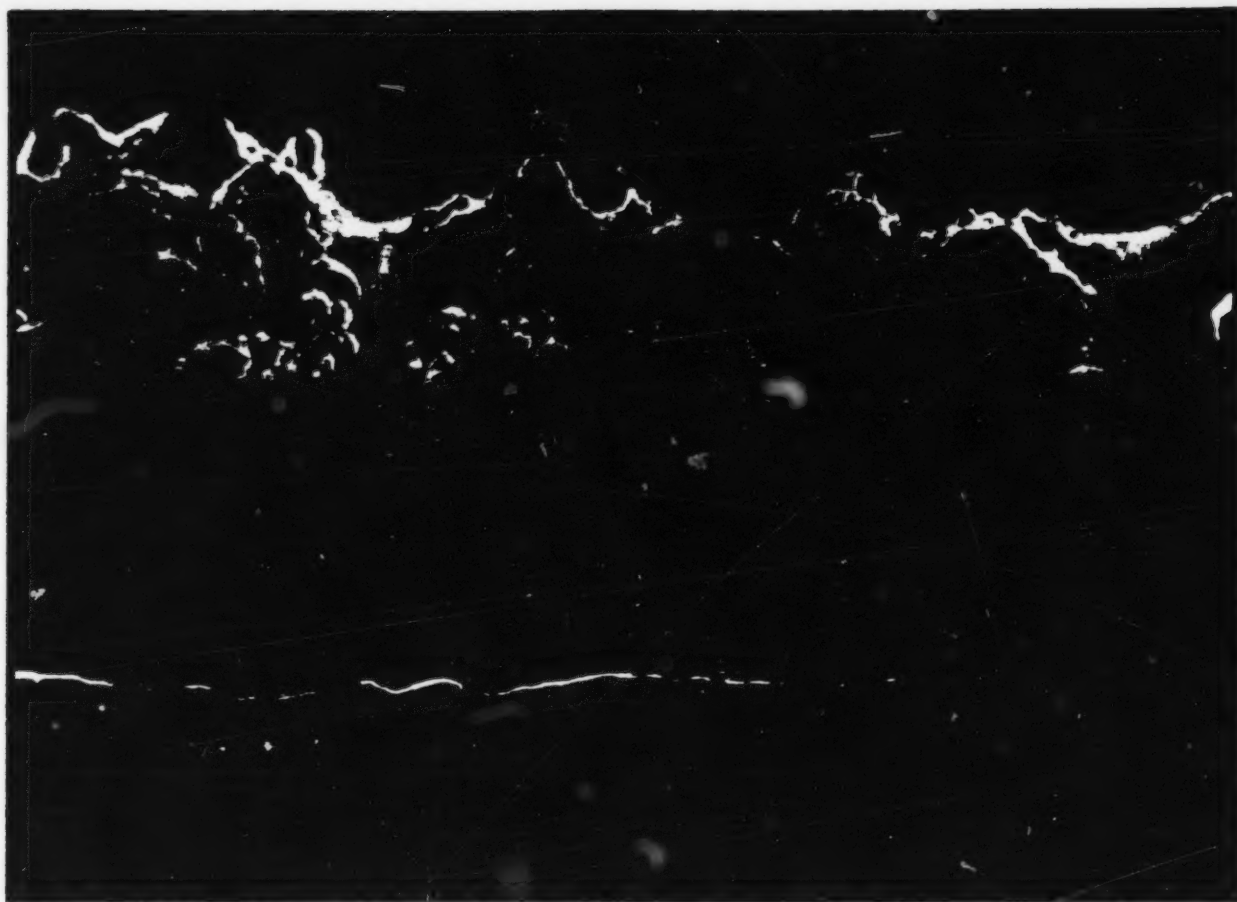


Figure 4: EDM Cut Edge, Melted/
Corroded Material
is Evident

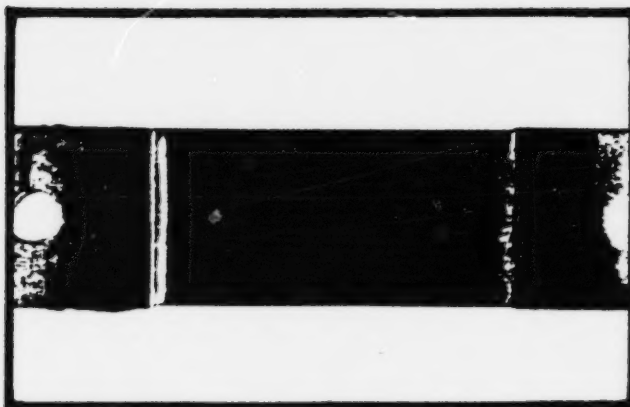


Figure 5: Test Specimen with Metal
Tabs at the End

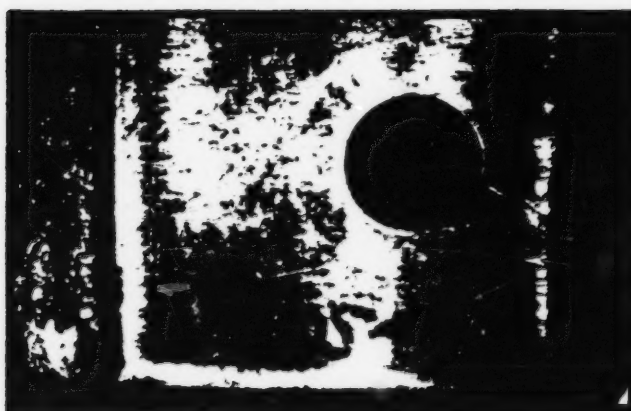


Figure 6: Punched Through Hole in
the Metal Tabs for
Alignment

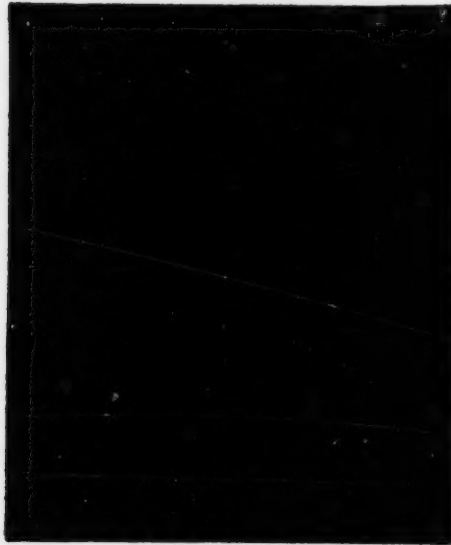


Figure 7: Self-Aligning Test
Fixture for Tensile and
Fatigue Testing



Figure 8: Test Being Done Immersed
in the Corrosive Liquid



Figure 9a: The Dull Side of the
Ribbon in Contact with
Quench Surface

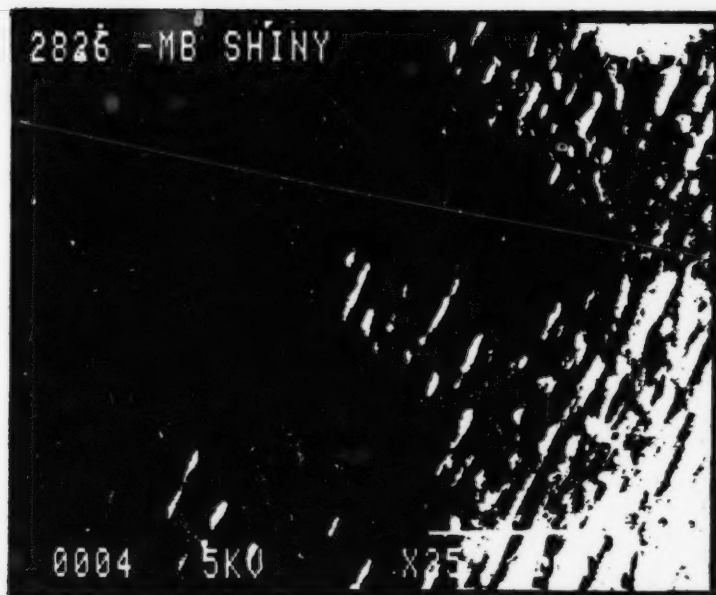


Figure 9b: The Shiny Side of the
Ribbon with Fish-Scale
Pattern

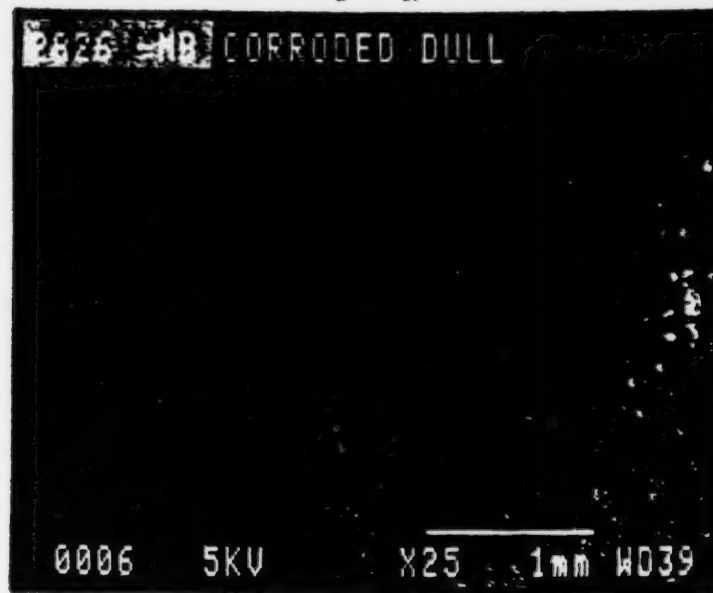


Figure 10: Corrosion of 2605-S2
in H₂SO₄ Solution

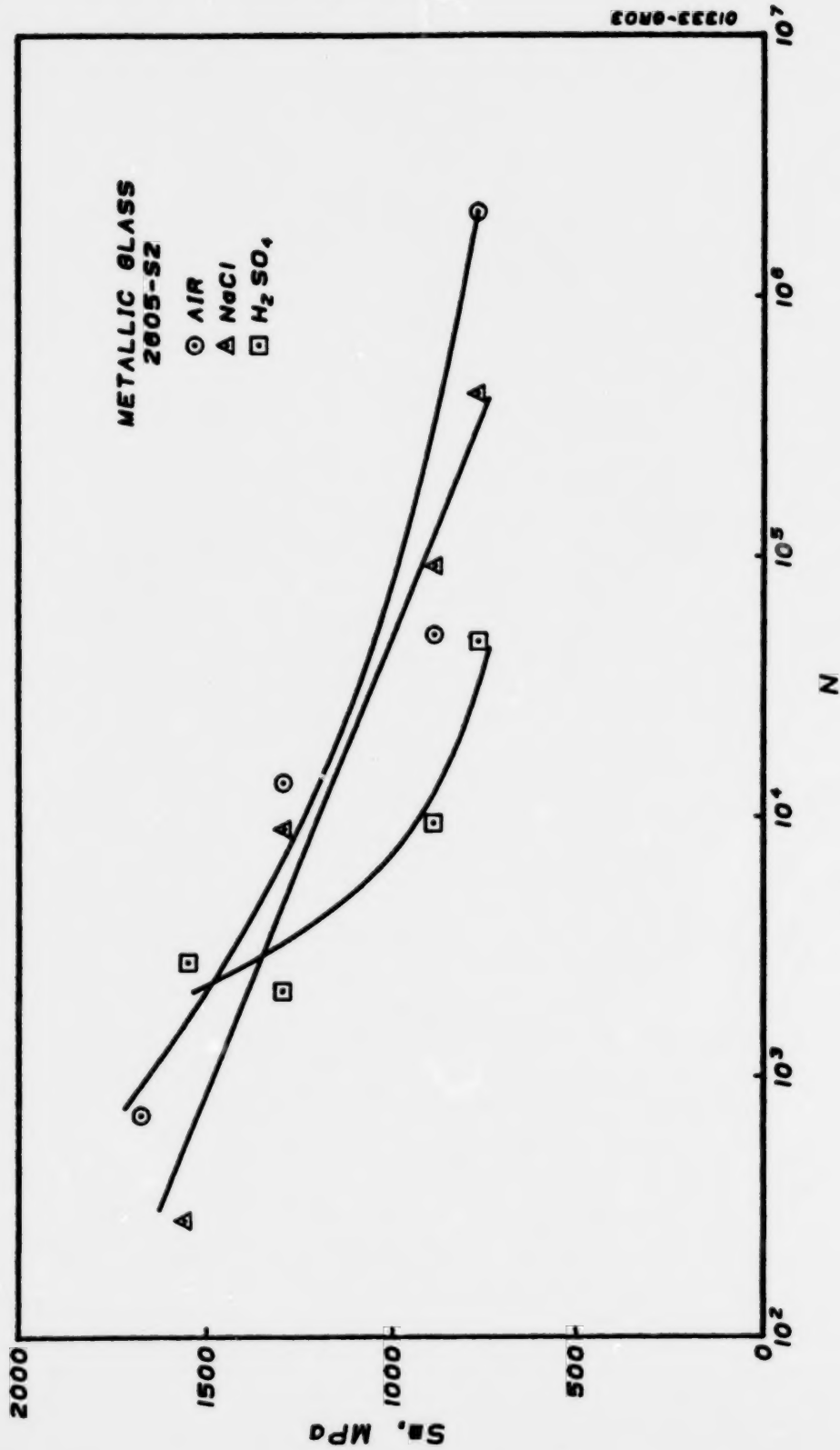
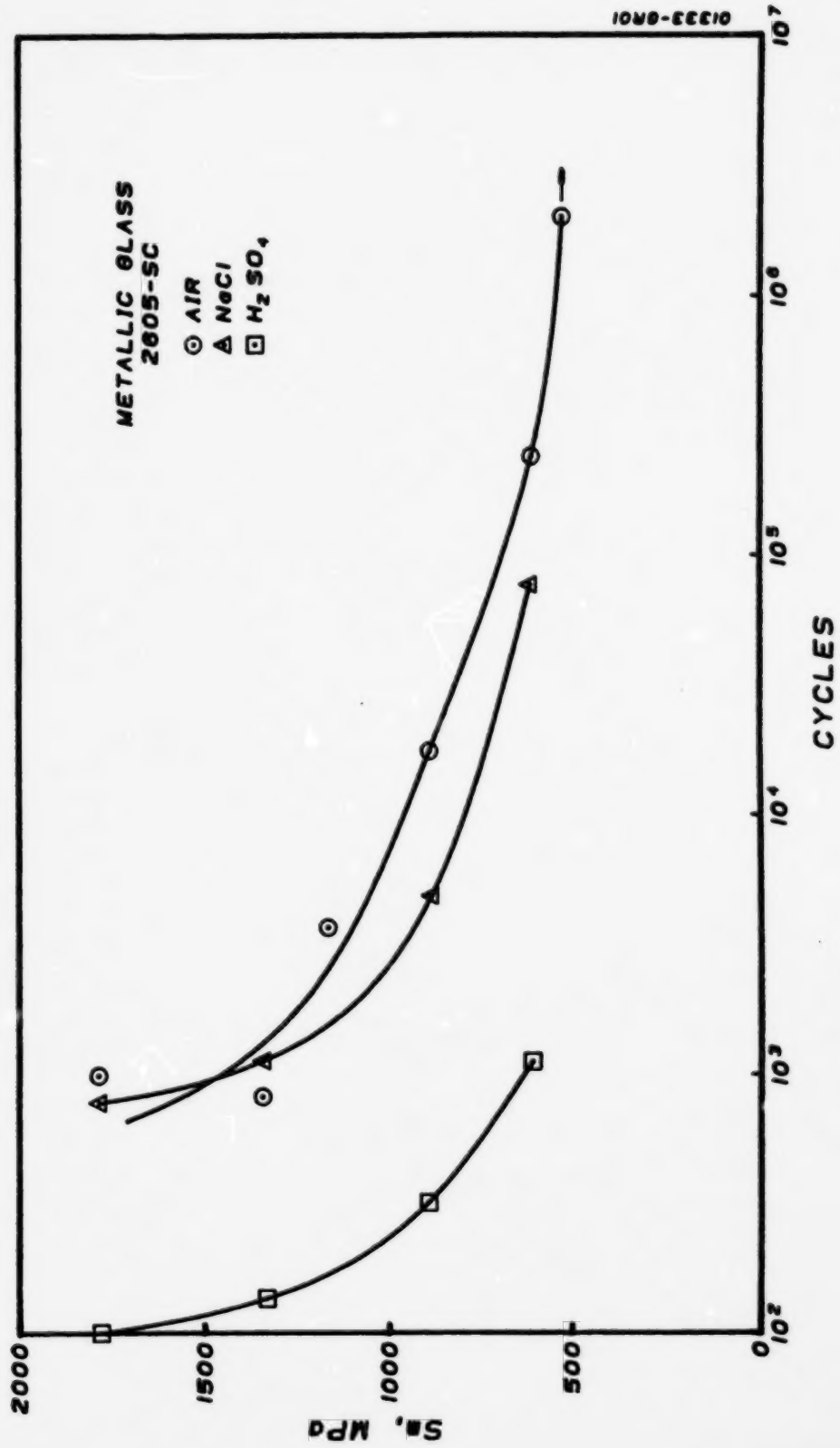
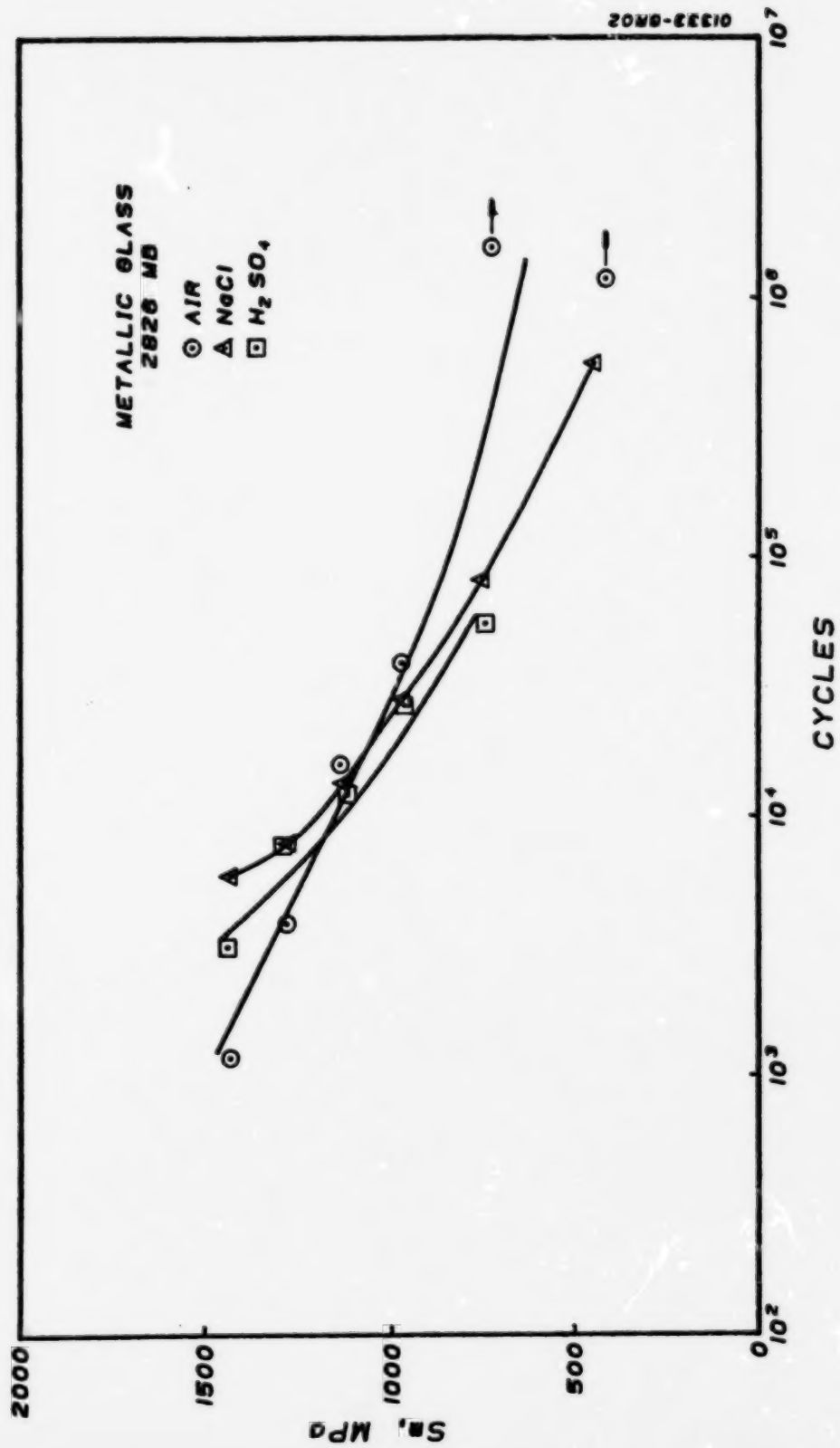


FIGURE: II



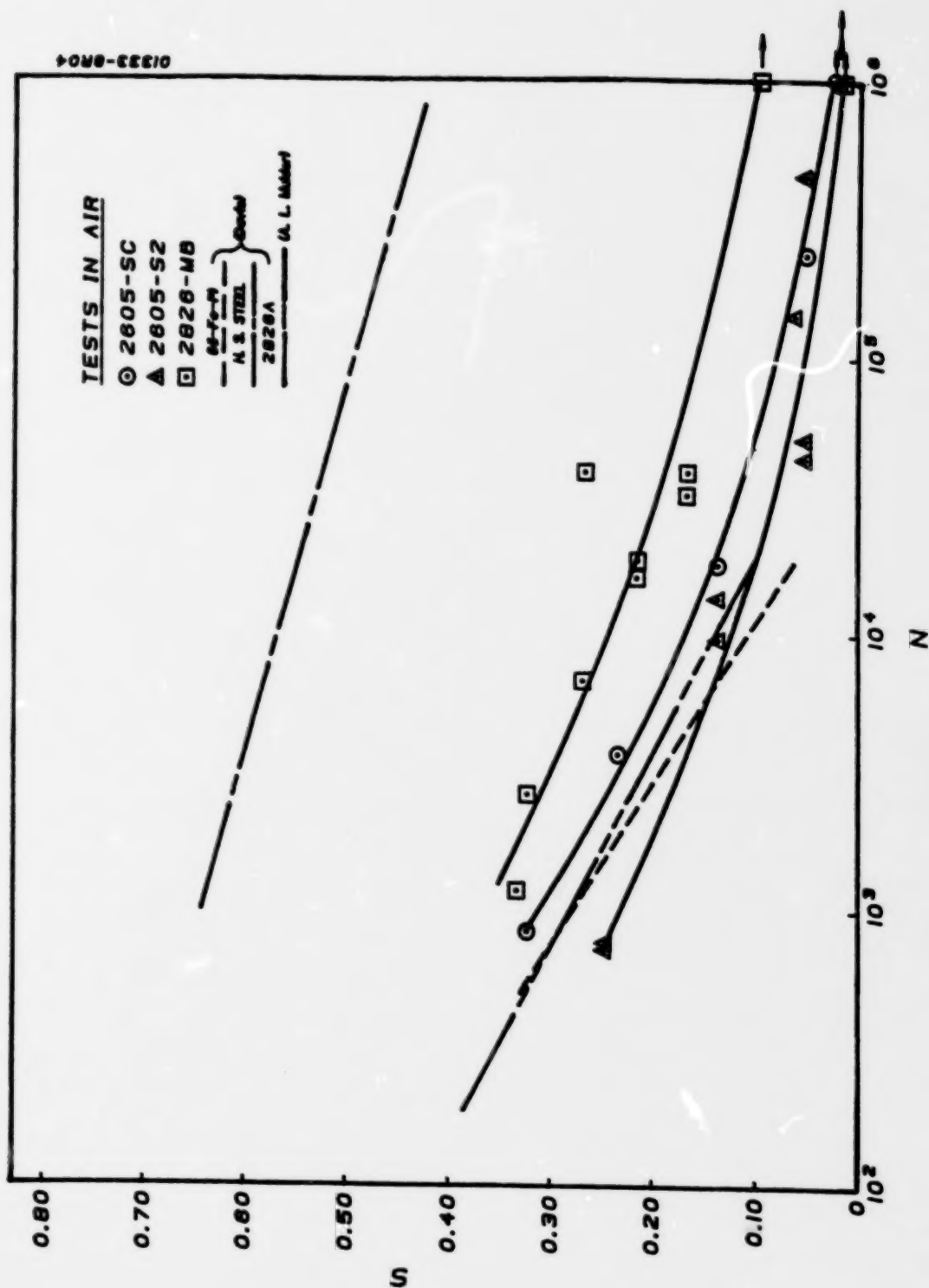
Sm vs Cycles to
Failure for 2605-SC
Alloy

FIGURE 12



Sm vs Cycles to
Failure for 2826-MB
Alloy

FIGURE: 13



Fatigue Data for Tests
in Air is Plotted for
Three Alloys

FIGURE: 14

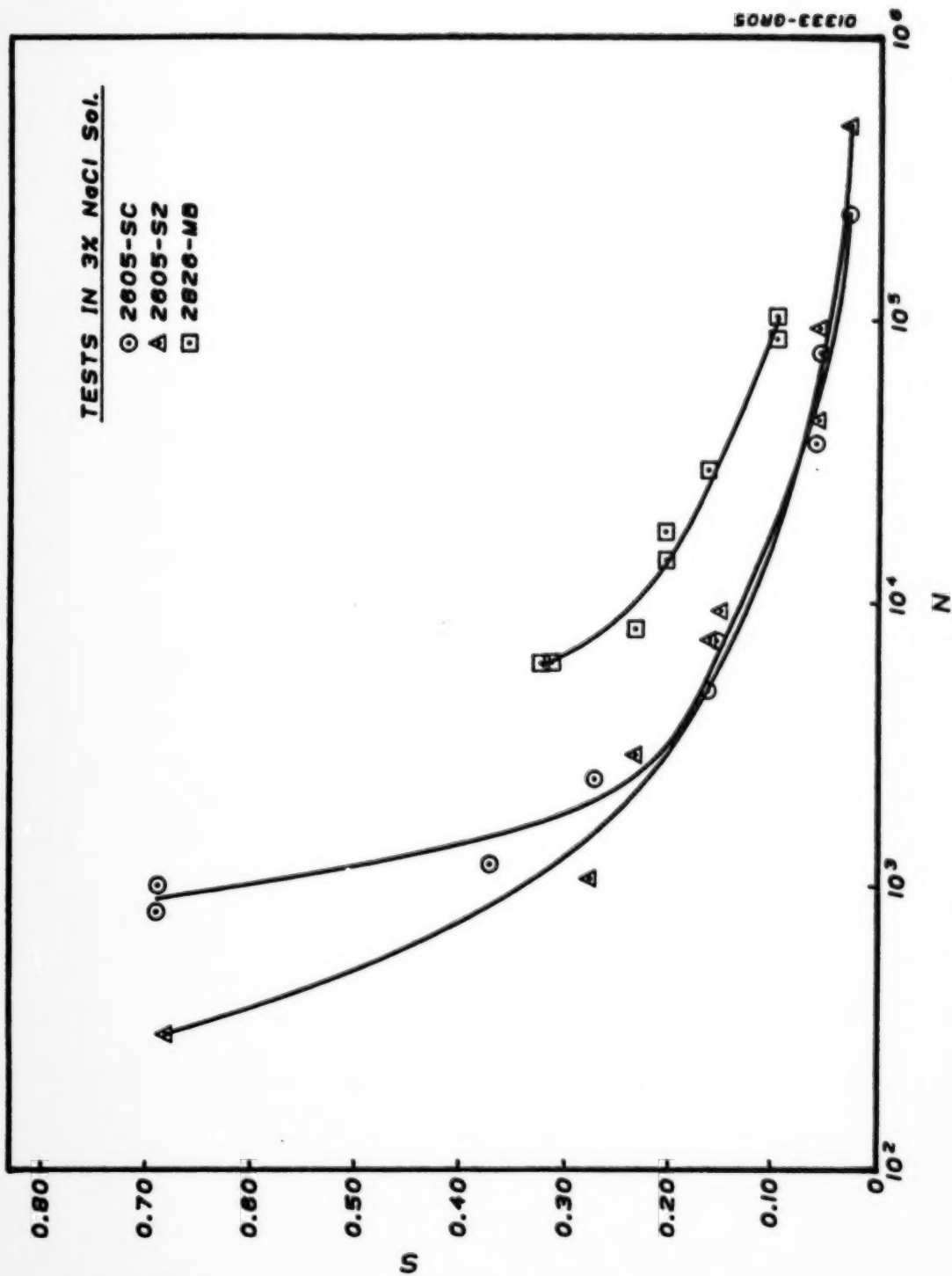
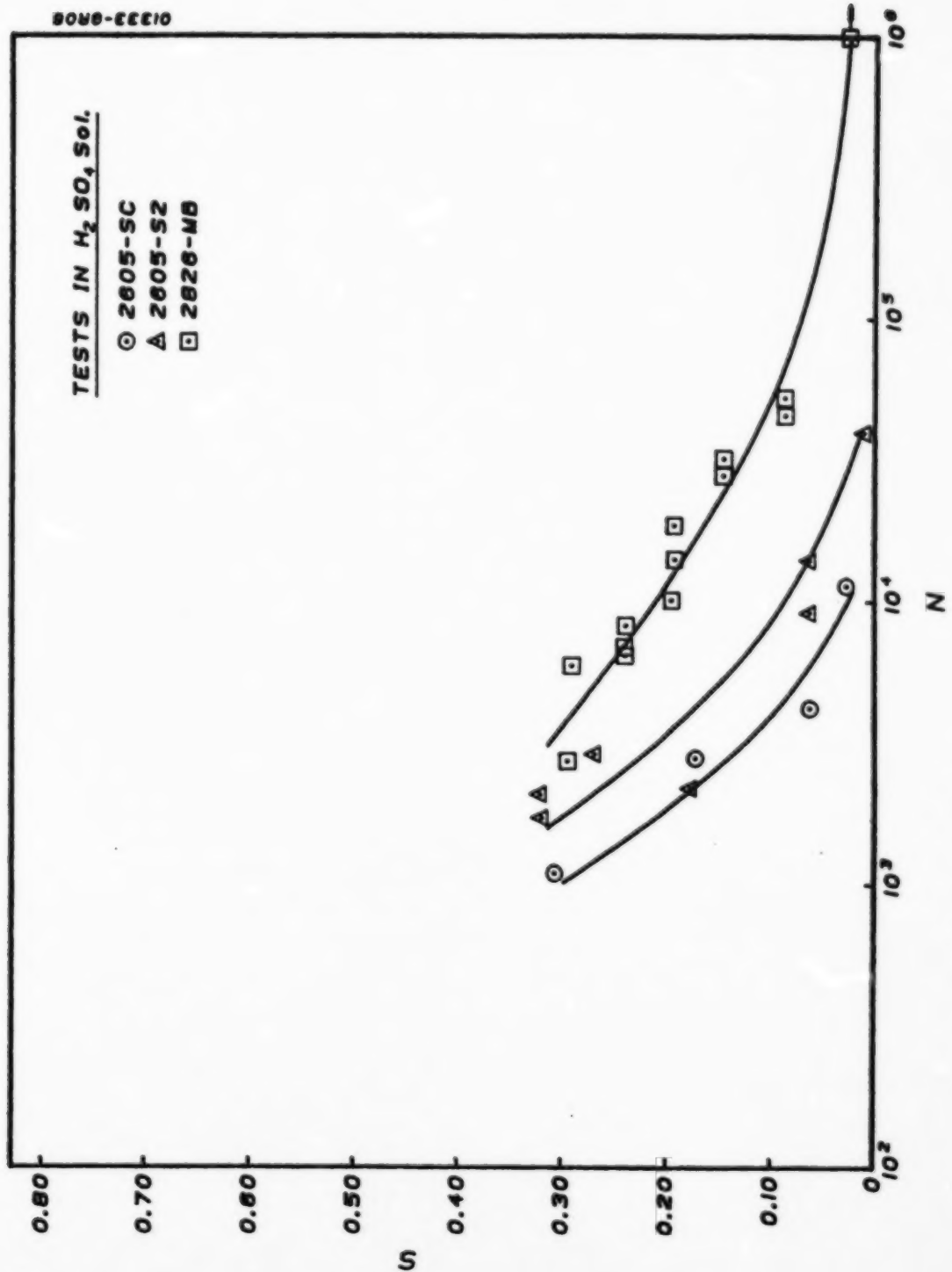


FIGURE: 15
Fatigue Data for Alloys
in NaCl Solution (3%)



Fatigue Data for
Alloys in H_2SO_4
Solution (3%)

FIGURE: 16

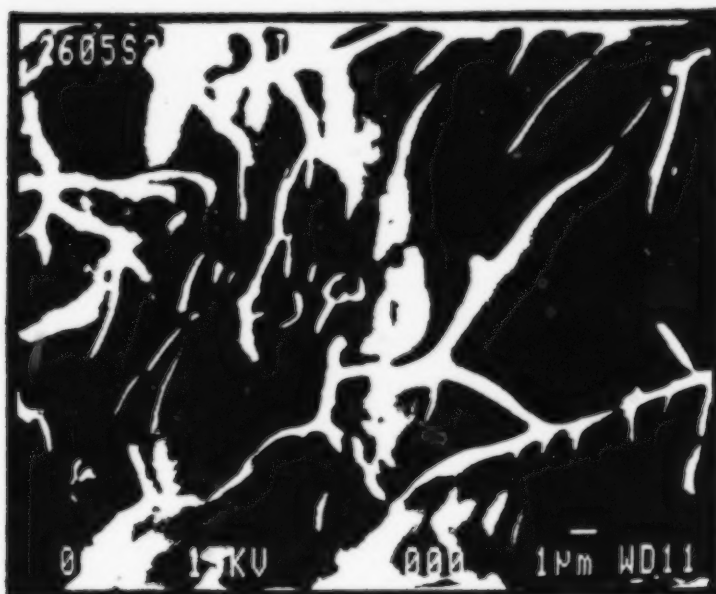


Figure 17a: Vein Pattern on a Fracture Surface

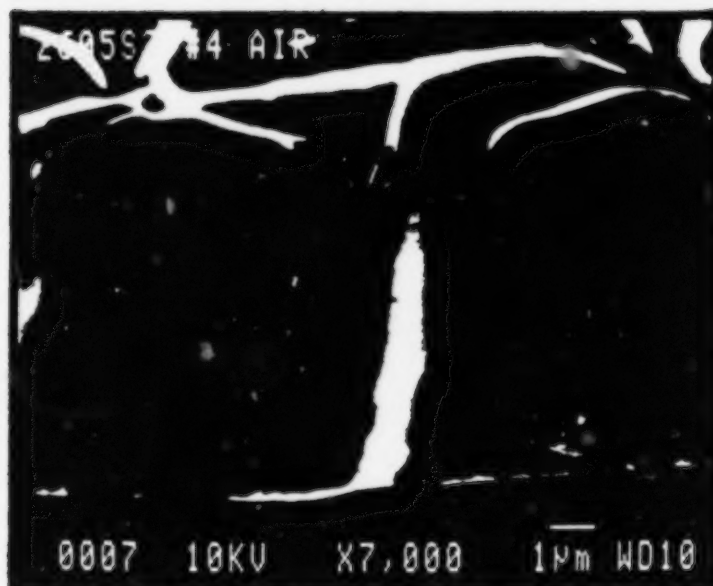


Figure 17b: Fatigue Striations
in 2605-SC Due to
Cyclic Stress

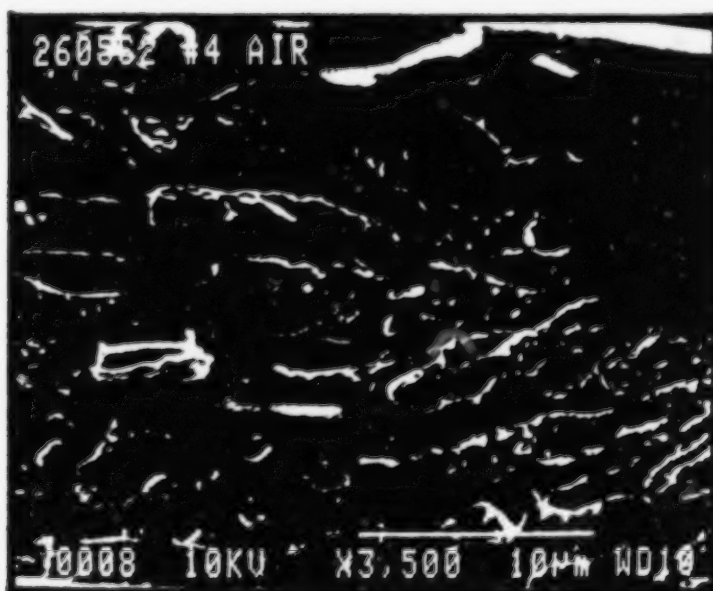


Figure 17c: Chevron Pattern Due
to Fast Crack Growth

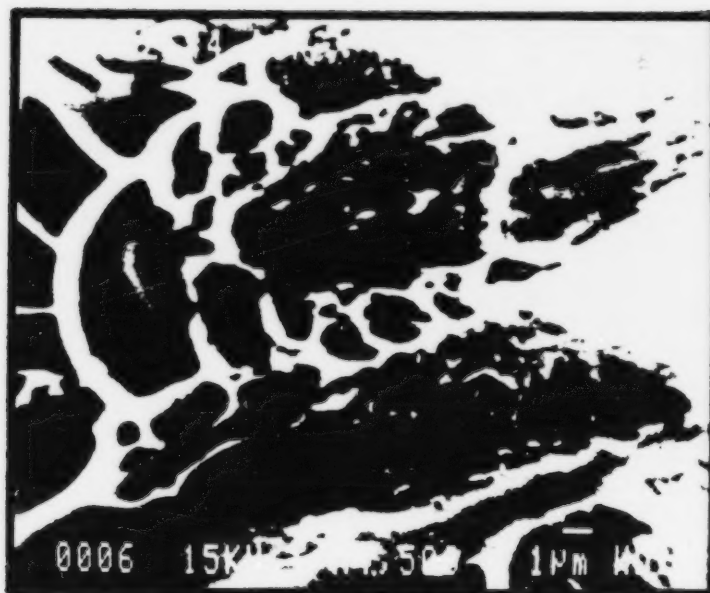


Figure 18a: An Area Where Dimples
(Ductile) Were Noted

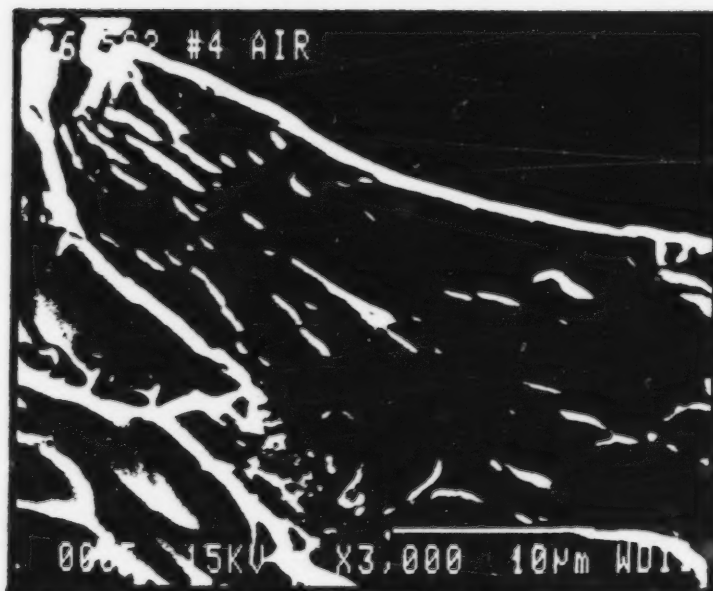


Figure 18b: Step Wise Fracture
Surface

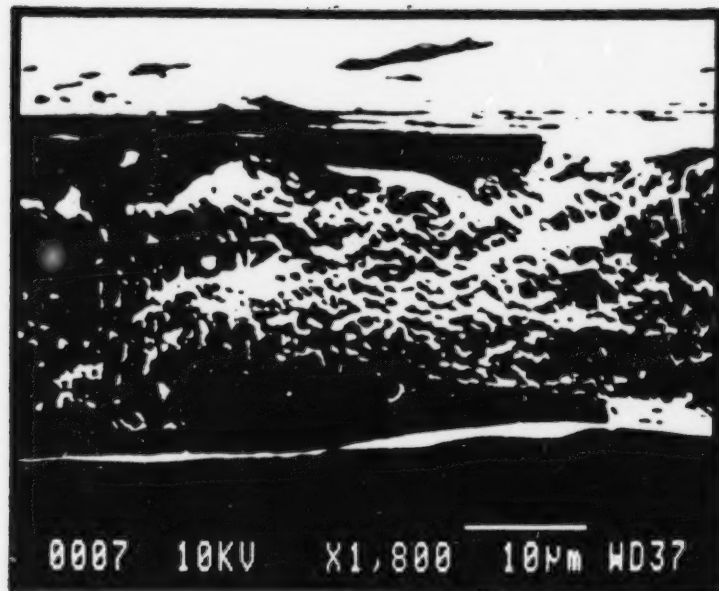


Figure 18c: Fine Fatigue
Striations with No
Vein Pattern

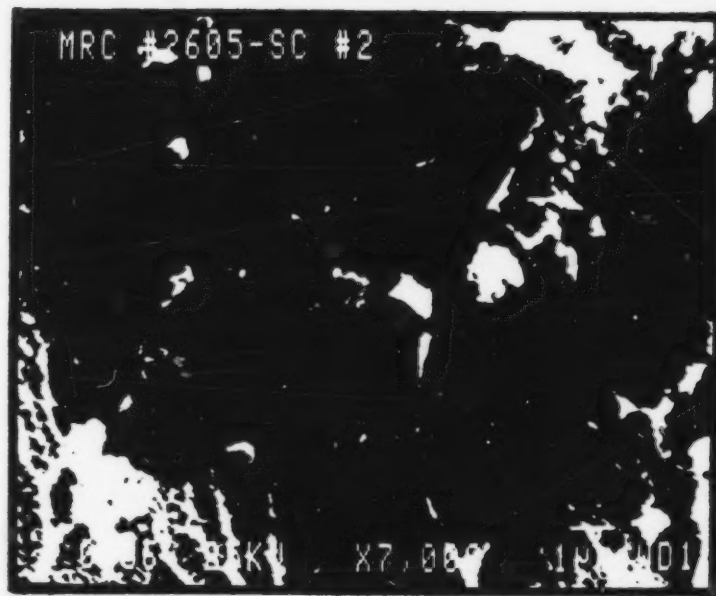


Figure 19a: Corroded Fracture
Surface In H_2SO_4

19 a

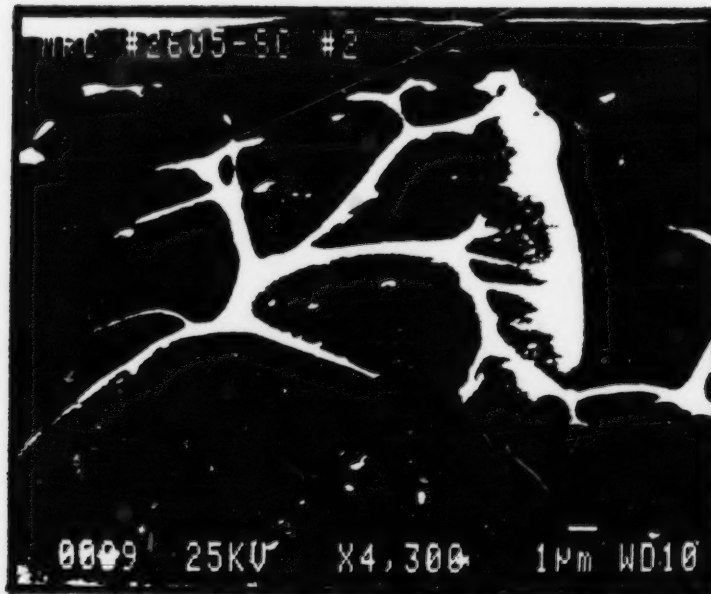


Figure 19b: Fatigue Striations
on Fracture Surface
in H_2SO_4 Tested
2605-SC Sample



Figure 19c: Fast Fracture Near
a Defect

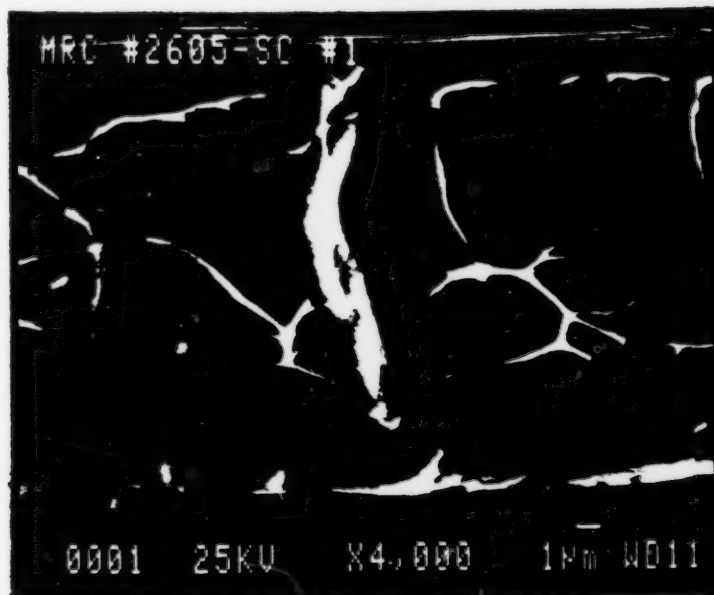


Figure 20a: Vein Pattern in
2605-SC Fatigue
Tested in NaCl

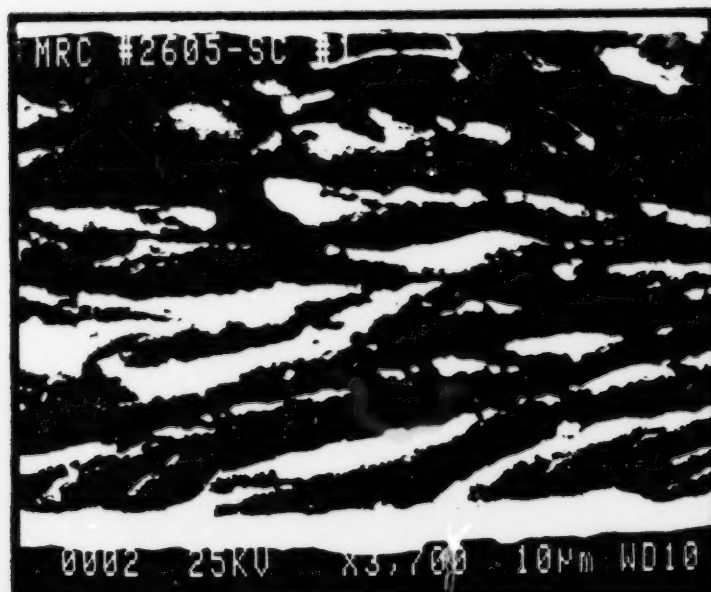


Figure 20b: Chevron Patterns as
Fast Fracture in
2605-SC

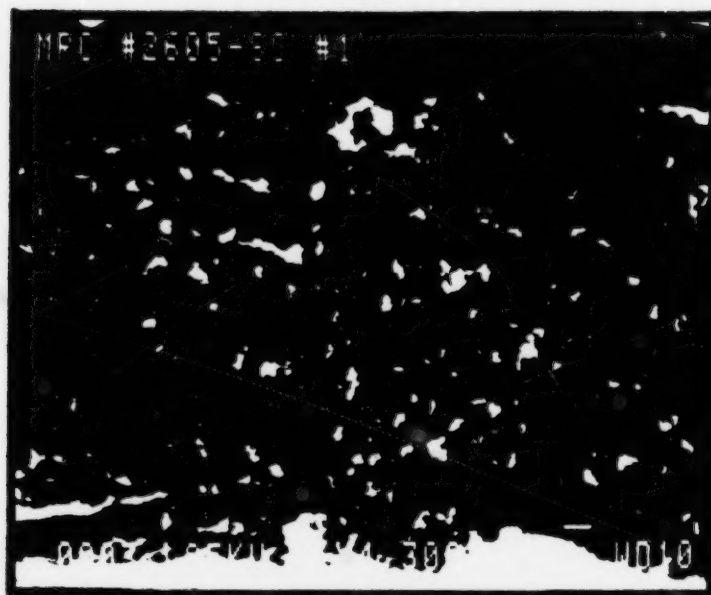


Figure 20c: General Corrosion in
2605-SC

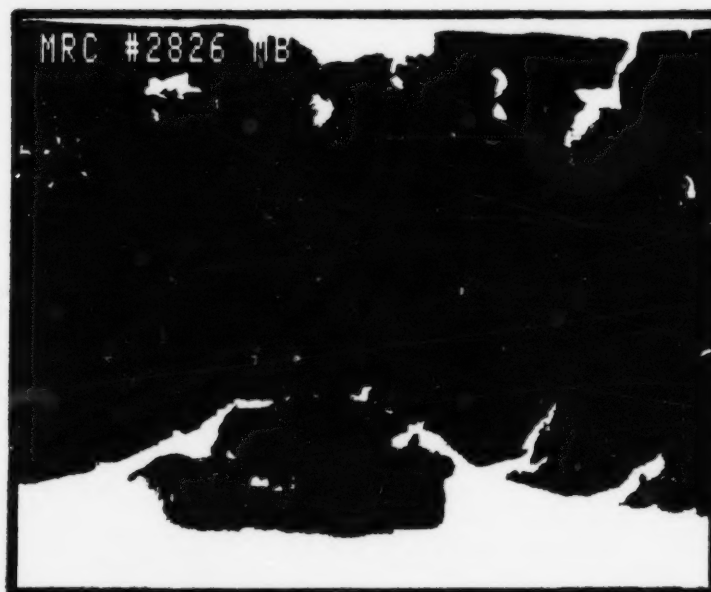


Figure 21: Surface Defect
Causing Fast Fracture